DELAMINATION IN BLAST RESISTANT LAMINATED GLASS

Mohammad Amin Samieian[1], David Cormie[2], David Smith[2], Will Wholey[2], Bamber R.K. Blackman[1], Paul A. Hooper[1], John P. Dear[1]

[1] Department of Mechanical Engineering, Imperial College London, SW7 2AZ, UK
[2] Arup Resilience Security & Risk, 13 Fitzroy Street, W1T 4BQ, UK

Keywords: Blast, Delamination, Laminated Glass, Sandwich composite

ABSTRACT

Laminated glass is used in structures for protection against blast loads. Laminated glass facilitates its safety mechanism through delamination of the glass from the interlayer. However, the amount of delamination is important. An experimental study has taken place to quantify the delamination energy in laminated glass composites. Through-cracked tensile tests on laminated glass and also tensile tests on the polymer interlayer alone have been carried out. The results were used to calculate an adhesive fracture energy. The tests were carried out at a temperature range of 20-60°C for three different interlayer thicknesses. The adhesive fracture energy was found to be independent of temperature and interlayer thickness for the range of temperatures tested.

1 INTRODUCTION

Laminated glass composite properties may change once environmental conditions diverge from the design point. In such laminates, a polyvinyl butyral (PVB) interlayer is sandwiched between layers of annealed glass. In some climates, air temperatures can reach up to 50°C and surface temperatures can exceed this value. As with most polymers, PVB's mechanical response is temperature dependant [1, 2]. This can lead to significant divergence in performance from the initial design and predictions.

Laminated glass is an important component in blast protective design. When an explosion occurs, the glass fractures almost instantly after blast waves interact with the window. Then the interlayer carries the loads through its deformation. Protection is provided when glass fragments stay adhered to the interlayer and thereby preventing the blast pressure from entering the building.

In a blast scenario, adhesion between the interlayer and the glass is important. Low adhesion will mean that sharp glass fragments detach from the interlayer and travel at high velocities, causing additional threats to the people in the vicinity. With high adhesion, displacements will be low, thus, leading to premature tearing of the interlayer. This is because for a greater displacement, a greater length of delaminated PVB is required. Therefore a balance between the two extremes is essential.

Common experiments usually associated with assessing adhesion are the peel and pummel test. The pummel test does not lead to an accurate result such as an adhesive strength for comparison; it is a subjective test and requires human judgement [3]. The peel test is a better approach than the pummel test, as it provides an adhesive fracture energy. Kinloch *et.al.* have provided a test method and analysis techniques for peeling of flexible laminates [4]. However, this method requires quantification of the energy lost via other routes, such as bending of the peel arm.

An alternative method that has recently been used to assess adhesion is the through-cracked tensile test. The glass is pre-cracked perpendicular to the loading direction on both sides of the laminate and tested in tension (Fig. 1). This removes the complications associated with bending of the peel arm. Several authors have previously worked on this [5-10]; some of which have not provided an accurate analysis of the fracture energy. Furthermore, issues such as strain rate and temperature dependency have not been addressed.

The through-cracked tensile test was originally used by Sha *et al.* [6] to characterise the adhesion between laminated glass and the PVB interlayer. They termed this test as the 'tension adhesion test'. Similarly, through cracked tensile tests were later used by Seshadri *et al.* [7] to assess the mechanical behaviour of cracked laminated glass. They stated that if the interlayer constitutive model is known, the interfacial fracture toughness and energy release rate can be calculated from the tensile tests on cracked laminated glass. Seshadri *et al.* [11] later extended their work by assuming a hyperelastic

material model to develop a finite element model which would allow analysis of more complex geometries other than the tensile specimens they tested.

Delince *et al.* [12], however, could not reproduce the experimental results of Seshadri. They proposed this was because the specimens spent a very short time in steady state delamination. They also did not successfully extend the method to other interlayers such as SentryGlas Plus (SGP).

The focus of the current study is to calculate an adhesive fracture energy for PVB at different temperatures. The glass thickness either side of the laminate was kept constant at 3 mm. Three different PVB interlayer thicknesses were considered, namely 0.76 mm, 1.52 mm and 2.28 mm. The experiments were carried out over a temperature range of 20-60°C.

The outline of this paper is as follows. The theory behind how the adhesive fracture energy is calculated is explained. This is followed by a description of the experimental setup for the through-cracked tests and the tensile tests on the interlayer. Finally the adhesive fracture energy is calculated from the experiments carried out and a discussion on how it varies with interlayer thickness and temperature is presented.

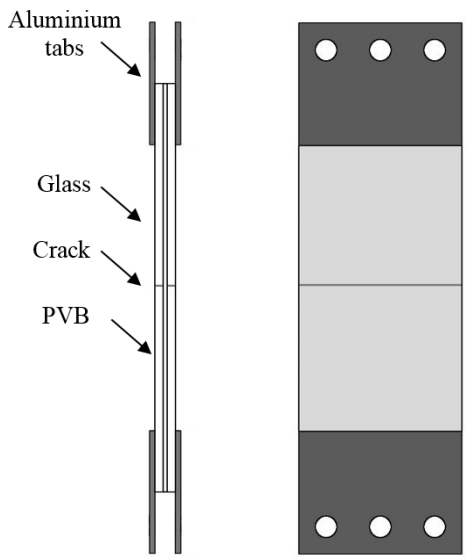

Figure 1: Schematic sketch of the through-cracked tensile test specimen.

2 THEORY

Kinloch *et al.* have followed an energy based analysis for calculating the adhesive fracture energy in the peel test [4]. Their analysis can be modified to allow the adhesive fracture energy to be calculated from the through-cracked tensile tests.

In the through-cracked tensile test, as the load is applied in tension, the interlayer begins to delaminate from the glass. The delaminated interlayer ligament carries the load undergoing tensile deformation (Fig. 2).

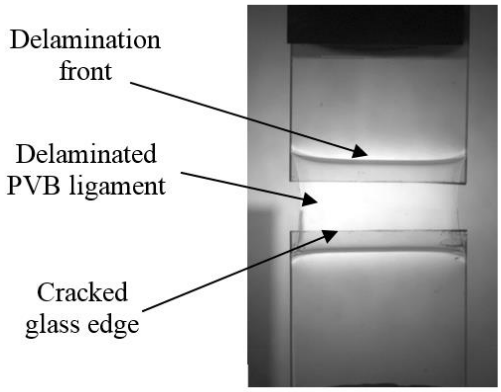

Figure 2: Specimen with 1.52 mm interlayer tested at 20°C at a test rate of 1 m/s, viewed through polarizing filters.

The adhesive fracture energy, G_a, in the delamination of the interlayer can be calculated through the following energy balance approach.

$$G_a = \frac{1}{b}\left(\frac{dU_{ext}}{da} - \frac{dU_s}{da} - \frac{dU_{dt}}{da}\right) \tag{1}$$

Where dU_{ext} is the external work, dU_s is the stored energy in the delaminated interlayer, dU_{dt} is the energy dissipated during the tensile deformation of the delaminated interlayer ligament, b is the sample width and a is the delamination length. The external work is calculated from the through-cracked tensile test. The stored energy and that of tensile deformation are calculated from tensile tests performed on unlaminated PVB.

The through-cracked tensile test is similar to a peel test conducted at a 0° loading angle. For an adhesive failure load, P, interlayer thickness, h, and sample width, b, undergoing a displacement $d\delta$, the energy terms can be calculated from Eqn. 2 and Eqn. 3 respectively.

$$dU_{ext} = Pd\delta = Pda\ \varepsilon_a \tag{2}$$

$$dU_s + dU_{dt} = bhda\int_0^{\varepsilon_a} \sigma\ d\varepsilon \tag{3}$$

Where σ is the stress and ε_a is the tensile strain in the delaminated interlayer ligament. The load, P, can be calculated as the load plateau from the through-cracked tensile test (shown as the dashed line in Fig. 3). The tensile strain in the PVB ligament, ε_a, can be calculated from the tensile test on the PVB as the strain corresponding to the stress caused by the load P.

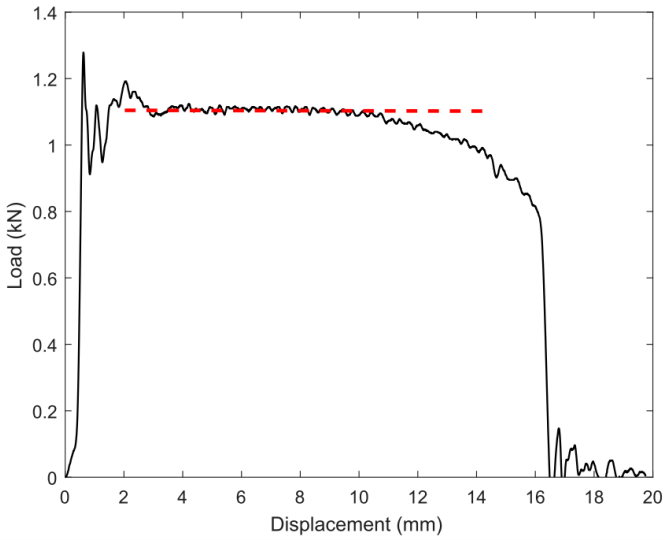

Figure 3: Through-cracked tensile test at 20°C for the 0.76 mm interlayer (dashed line represents the adhesive failure load, *P*)

The adhesive fracture energy can be determined by substituting the energy terms from Eqn. 2 and Eqn. 3 into Eqn. 1. The final G_a value for the through-cracked tensile tests is obtained as a quarter of the G_a value in Eqn. 4. This is because in the through-cracked test, as the load is applied, four new crack surfaces (delamination surfaces) are formed.

$$G_a = \frac{P}{b}(\varepsilon_a) - h\int_0^{\varepsilon_a} \sigma \, d\varepsilon \tag{4}$$

3 EXPERIMENTAL METHODS AND DATA ANALYSIS

3.1 Through-cracked tensile test

The test specimens were prepared from two plies of 3 mm annealed glass laminated together with PVB. Three different PVB interlayer thicknesses were used, namely 0.76 mm, 1.52 mm and 2.28 mm. A total of 19 specimens were tested (Table 1). The dimensions of the specimen were 150 mm long by 60 mm wide. A single coincident crack was created perpendicular to the loading direction on both sides of the specimen. For tests where a repeat was performed, an average was taken for the adhesive failure load. Tests were conducted in the temperature range of 20-60°C.

Table 1: Number of through-cracked tensile specimens tested at each condition.

Thickness of PVB (mm)	**Temperature (°C)**				
	20	**30**	**40**	**50**	**60**
0.76	2	1	1	1	1
1.52	2	1	1	1	2
2.28	1	2	2	1	-

The experiments were carried out at a test speed of 1 m/s. At room temperature for the 0.76 mm interlayer this corresponds to a strain rate of 21 s^{-1} in the delaminated ligament. This is a representative value compared to the maximum strain rate the laminated pane experiences under blast conditions [13].

The experiments were carried out using an Instron high rate servo-hydraulic testing machine (Fig. 4). The load was applied through a lost-motion device; this allowed for the loading train to accelerate to the desired velocity prior to pulling the sample. The load was measured using a piezoelectric load cell (PCB model 222B). To ensure uniform temperature across the sample, it was placed in an Instron

environmental chamber and was soaked for 24 hours prior to testing. The air temperature was measured using sensors built into the environmental chamber to ±0.5°.

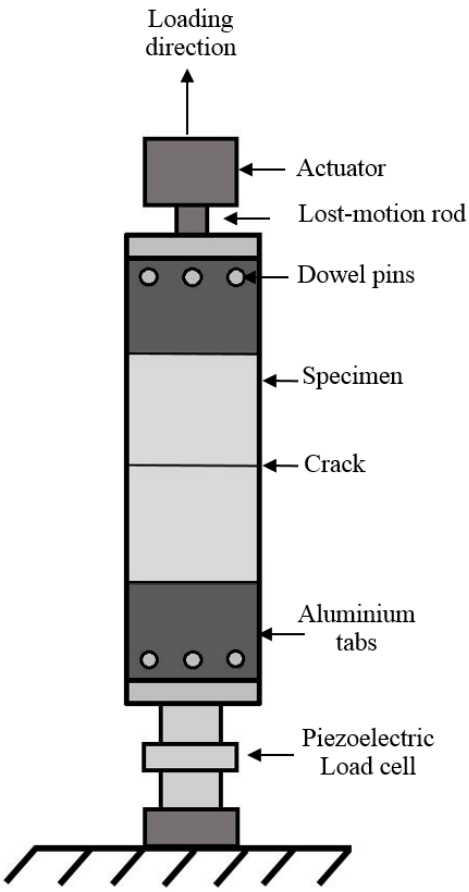

Figure 4: Through cracked tensile test setup.

3.2 PVB Tensile test

Tests on the PVB material (unlaminated) were conducted at a speed producing a similar strain rate to the through cracked tensile tests (Fig. 5). The tests were conducted at an approximate velocity of 1 m/s; this corresponds well with the strain rate in the through cracked tensile tests. The tests were conducted at a temperature range of 20-60°C. Three repeats were conducted at every temperature.

The load was measured using a piezoelectric load cell (PCB model 208A03). The displacement was measured using optical techniques. High speed video recording and image processing on MATLAB was used to track the marked lines on the sample representing the gauge length.

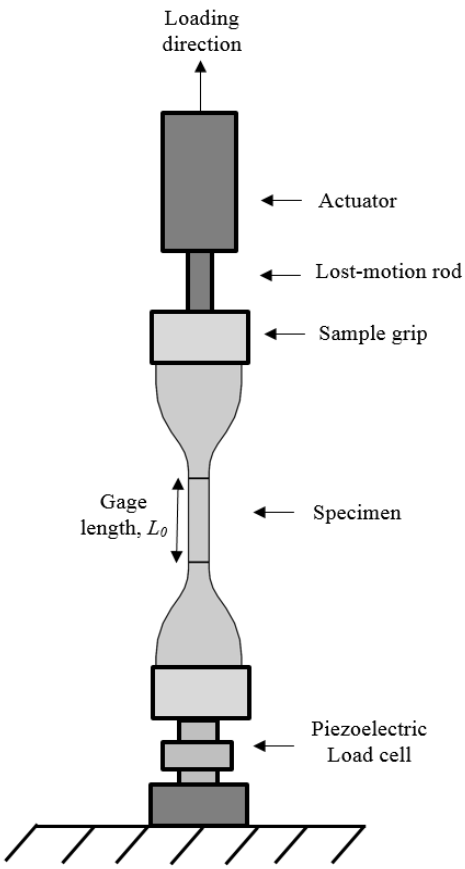

Figure 5: PVB Tensile test setup.

The specimen was punched out with a die (Fig. 6), according to dimensions given in the ASTM standard D 638 - 02a [14]. The thickness of the specimen was 0.76 mm.

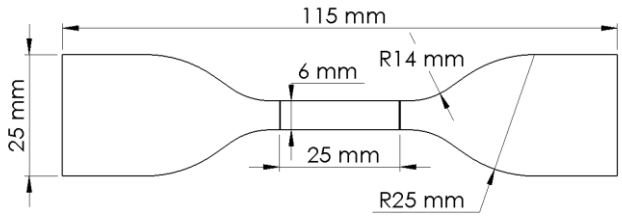

Figure 6: PVB tensile test sample dimensions.

4 RESULTS AND DISCUSSION

4.1 Through-cracked and tensile tests

The adhesive failure load was found to drop with temperature increase (Fig. 7). At higher temperatures, the polymer is more compliant (less stiff). This results in lower forces for a given displacement. The thicker interlayers generally showed greater adhesive load, an account of their greater effective stiffness.

As the temperature increases, the thickness of the interlayer becomes less important. At room temperature, the difference in adhesive loads between the three interlayers are much greater than at 50°C or 60°C.

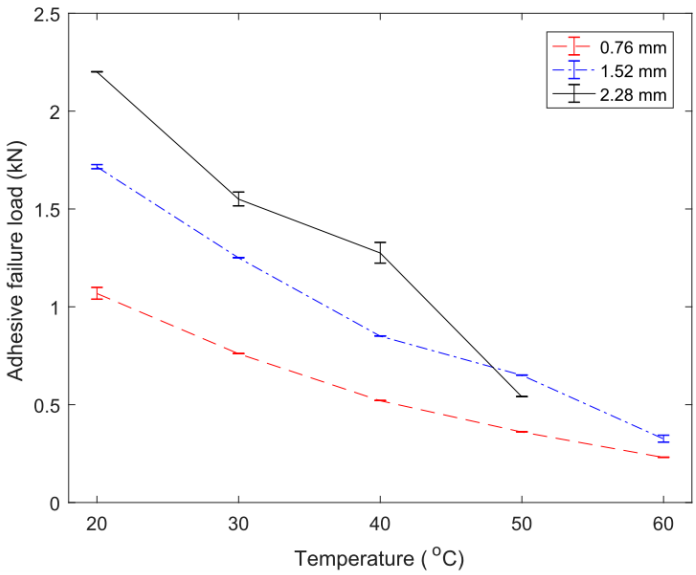

Figure 7: Adhesive failure load against temperature.

A typical result from the tensile tests is shown in Fig. 8. There is a steep rise in stress up to a certain value (approximately 4 MPa in this case). After this value, the rate of increase of stress is reduced by about an order of magnitude for a given strain. This behaviour is as expected for the viscoelastic materials such as PVB [2].

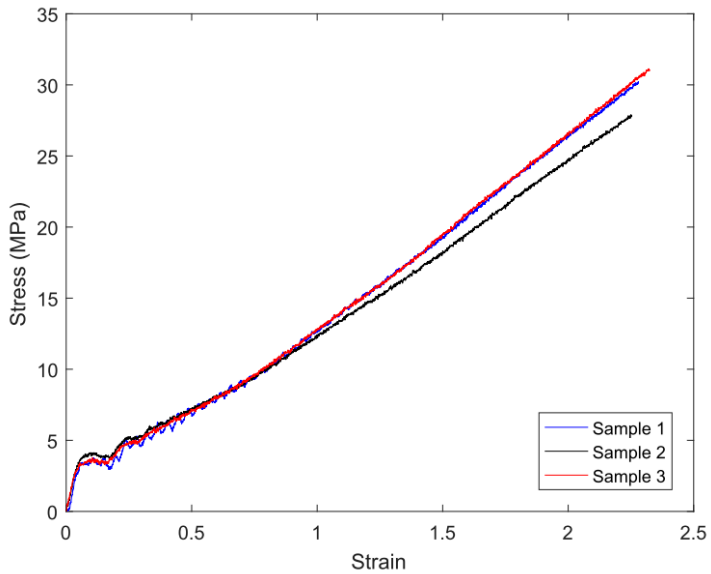

Figure 8: Engineering stress against engineering strain with three repeats (1 m/s at 30°C).

4.2 Adhesive fracture energy

Through the use of the load value from the through-cracked tensile tests, an adhesive fracture energy value was calculated for each repetition of the tensile tests at all conditions. An average was taken and the data were plotted against temperature for every interlayer thickness with error bars representing one standard deviation (Fig. 9).

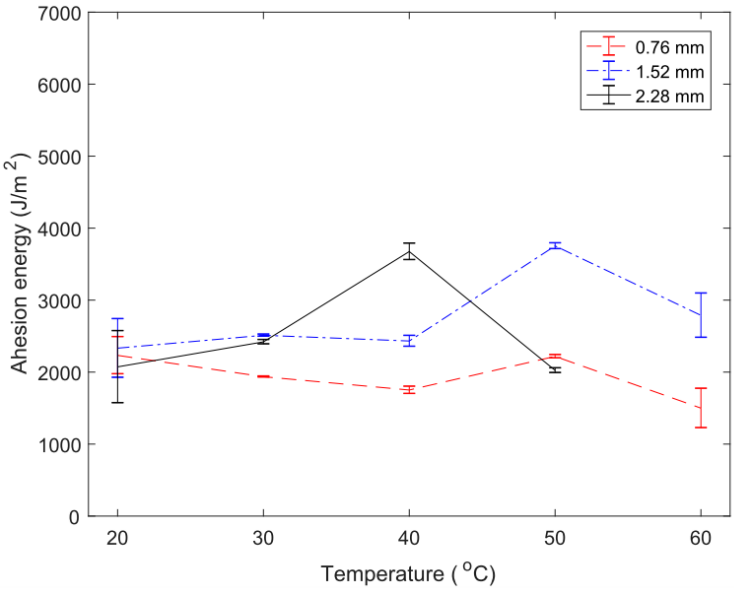

Figure 9: Adhesive energy against temperature for different interlayers.

Del Linz *et al.* developed a model based on experimental data to calculate the adhesion energy at room temperature [5]. Based on this model, at a rate of 20 s^{-1} it is estimated that the adhesive fracture energy is 2800 J/m^2. This is in good agreement with the results from the experiments carried out.

Despite the fact that the 1.52 mm interlayer is consistently above that of the 0.76 mm interlayer, from the results obtained in this experiment, the adhesive fracture energy is shown to be thickness independent. This is because as the thickness was increased to 2.28 mm, similar trends could not be observed.

Similarly in the temperature range tested, the adhesion energy also demonstrated to be temperature independent. The adhesive energy becomes more dispersed between the different interlayers as the temperature increases. This could be because the sample spent a much lower time in the steady state. At greater temperatures, the interlayer is more compliant. This resulted in a much greater deformation of the interlayer compared to the steady state propagation of the delamination front.

5 CONCLUSION

In this study the influences of temperature and interlayer thickness on the adhesive energy of PVB were studied. The effect of increasing the temperature from 20°C to 60°C on the adhesive energy did not show a clear trend. Moreover, the change of interlayer thickness did not show a clear corrolation with adhesive energy. However as the temperature was increased, the spread in data between the different interlayer thicknesses showed an increase. Further repetitions of the through-cracked tensile tests will assist to validate the results at higher temperature, where a lower fraction of the test was spent in the steady state delamination region. Future work will include quantification of adhesion for a greater temperature range and also different strain rates.

For purposes of practical applications, it can be deduced that the adhesion between the glass and PVB will not vary significantly in the temperatures tested. Therefore it is reasonable to assume that apart from any influence of stiffness, the amount of sharp glass fragments that will stay adhered at higher temperatures will be similar to that of the design conditions.

However, the more important factor is how much energy the cracked laminate can absorb from the blast load without tearing. Quantification of the load and displacement capacities of the interlayer at higher temperatures in future studies will help in the understanding of the post-crack response of the laminated glass at higher temperatures.

ACKNOWLEDGEMENTS

The authors would like to thank the EPSRC (the Engineering and Physical Sciences Research

Council) and Arup Resilience, Security and Risk for financially supporting Mohammad Amin Samieian since the beginning of his PhD. The Authors are also grateful to Leroy Reed at Kite Glass (UK) for providing the laminated glass and PVB material.

REFERENCES

[1] W. Callister, D. Rethwisch, Materials science and engineering, 8th Edition, John Wiley & Sons, New York, 2011.

[2] P. Hooper, B. Blackman, J. Dear, The mechanical behavior of poly (vinyl butyral) at different strain magnitudes and strain rates, J Mater Sci, **47**, 2012, pp. 3564–3576 (doi: 10.1007/s10853-011-6202-4).

[3] S. Huo, H. Reis, Estimation of adhesive bond strength in laminated safety glass using guided mechanical waves: Part I. An energy velocity approach, *Insight: Non-Destructive Testing and Condition Monitoring*, **50**(3), 2008, pp. 146-152 (doi: 10.1784/insi.2008.50.3.146).

[4] A.J. Kinloch, C.C. Lau, J.G. Williams, The peeling of flexible laminates, *International Journal of Fracture*, **66**, 1994, pp. 45-70 (doi: 10.1007/BF00012635).

[5] P. Del Linz, P.A. Hooper, H. Arora, Y. Wang, D. Smith, B.R.K. Blackman, J.P. Dear, Delamination properties of laminated glass windows subject to blast loading, *International Journal of Impact Engineering*, **105**, 2017, pp. 39-53 (doi: 10.1016/j.ijimpeng.2016.05.015).

[6] Y. Sha, C. Y. Hui, E. J. Kramer, P. D. Garrett, J. W. Knapczyk, Analysis of adhesion and interface debonding in laminated safety glass, *Journal of Adhesion Science and Technology*, **11**, 1997, pp. 49–63 (doi: 10.1163/156856197X01010).

[7] S. Muralidhar, A. Jagota, S. J. Bennison, S. Saigal, Mechanical behaviour in tension of cracked glass bridged by an elastomeric ligament, *Acta Materialia*, **48**, 2000, pp. 4577–4588 (doi: 10.1016/S1359-6454(00)00244-5).

[8] R. Iwasaki, C. Sato, J. Latailladeand, P. Viot, Experimental study on the interface fracture toughness of PVB (polyvinyl butyral)/glass at high strain rates, *International Journal of Crashworthiness*, **12** (3), 2007, pp. 293–298 (doi: 10.1080/13588260701442249).

[9] J. Franz, J. Schneider, Through cracked tensile tests with polyvinylbutyral (PVB) and different adhesion grades, in: Engineering transparency, *International conference at glasstec*, 2014, pp. 135–142.

[10] C. Butchart, M. Overend, Delamination in fractured laminated glass, *Engineered transparency, International Conference at Glasstec, 2012.*

[11] M. Seshadri, S.J. Bennison, A. Jagota and S. Saigal, Mechanical response of cracked laminated plates, *Acta Materialia*, **50**, 2002, pp. 4477-4490 (doi: 10.1016/S1359-6454(02)00255-0).

[12] D. Delince, D. Sonck, J. Belis, D. Callewaert, R. Van Impe, Experimental investigation of the local bridging behaviour of the interlayer in broken laminated glass, *International symposium on the application of architectural glass, Munich*, 2008, pp. 41-49.

[13] P. A. Hooper, Blast performance of silicone bonded laminated glass, *PhD Thesis, Department of Mechanical Engineering, Imperial College London*, 2010.

[14] ASTM standard D638-02A, Standard test method for tensile properties of plastics, *ASTM International, West Conshohocken, PA*, 2003 (doi: 10.1520/D0638-02A).